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ON THE POSSIBLE ROLE OF NEON AND ARGON METASTABLE STATES IN THE AURORA AFTERGLOW

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SUMMARY

Considered in the present paper is the role of collision processes of molecules O_2 with atoms Ne and Ar in metastable states, leading to molecule O_2 dissociation with formation of excited oxygen atoms. Oxygen lines λ 5577 and 6300 Å are emitted at collisions with argon and O_2 lines λ 8446 and 7774 Å with neon. The duration of afterglow may reach several seconds at heights of $\sim$ 200 km.

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* *

At collision of an excited atom with a molecule, the latter may dissociate in such a fashion, that one of its constituent atoms is found to be in excited state. This process is responsible for the inverse population in quantum generators on the mixture of molecular oxygen with ideal gases [1]. For example, the dissociation of the oxygen molecule at collision neon atoms in the metastable state 3^3P_0** may lead to the formation of an atom O in excited states 3^3P and 3^5P

$$\mathrm{Ne}(3^3P_0) + \mathrm{O}_2 \rightarrow \mathrm{Ne}(2^1S) + \mathrm{O}(2^3P) + \mathrm{O}(3^3P,\ 3^5P). \qquad (1)$$

(The energy of the excited level s^3P Ne constitutes 16.7 ev, the dissociation energy of O_2 is 5.09 ev, the excitation energy of the oxygen level 3^3P is 10.9 ev and of the 3^5P — 10.7 ev). The transitions $3^3P - 3^3S$ give the atomic oxygen emission line λ 8446 Å, on which the generation was obtained.

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* O VOZMOZHNOY ROLI METASTABIL'NYKH SOSTOYANIY NEONA I ARGONA V PROTSESSAKH POSLESVECHENIYA POLYARNYKH SIYANIY.

** In the jl-binding scheme, most convenient for describing the Ne spectrum, this state is denoted $2p^5(P_{1/2})3s[1/2]_0$. For the sake of simplicity we shall utilize below 3^3P_0 for denoting the LS-binding scheme.

Processes of such a type may also play a specific part in the excitation of some spectral lines in polar aurorae, in particular, the line λ 8446 Å. By comparison with the earlier considered ones [2, 3], this excitation mechanism is endowed with a series of characteristic peculiarities linked in the first place with the prolonged lifetime of metastable states. We shall demonstrate this on an example of oxygen line's 8446 Å glow in conditions of bright and moving shapes of aurorae, excited by electrons.

When the flux of electrons intrudes the atmosphere, the excitation of the metastable state of neon $3^3 P_0$ is described by the equation

$$\frac{d[\mathrm{Ne}^*]}{dt} = W[\mathrm{Ne}] - [\mathrm{Ne}^*]\left(\frac{1}{\tau_0} + \frac{1}{\tau}\right), \tag{2}$$

where [Ne], [Ne*] are the concentrations of Ne atoms in the ground and metastable states; $W = n_e \langle v_e \sigma_e \rangle$ is the probability of excitation by electrons; n_e and v_e are respectively the concentration and the velocity of electrons; σ_e is the effective excitation cross section of the $3^3 P_0$ by electron impact (the brackets mean averaging by velocities); $1/\tau$ is the probability of breakdown of metastable states $3^3 P_0$ on account of the process (1); $1/\tau_0$ is the probability of all the remaining processes of that state's damping. It is essential, that the probability of radiative decay of neon state $3^3 P_0$ is zero, inasmuch as the transitions $3^3P_0 - 2^1S_0$ are forbidden for the electric as well as for the magnetic radiations of any multipole order. That is why the value of $1/\tau_0$ is entirely determined by second kind collisions with electrons and other atmosphere particles. The quantity $1/\tau$ is determined by the correlation

$$\frac{1}{\tau} = \langle v\sigma \rangle [O_2], \tag{3}$$

where $[O_2]$ is the concentration of molecules O_2; σ is the effective cross section of the process (1); v is the relative velocity.

Assume that p is the share of processes (1) leading to the excitation of the 3^3 P level of oxygen. Then the concentration of excited oxygen atoms [O*] at the 3^3P level will be determined by the equation

$$\frac{d[\mathrm{O}^*]}{dt} = q + \frac{p}{\tau}[\mathrm{Ne}^*] - A[\mathrm{O}^*]. \tag{4}$$

Here p/τ [Ne*] and q are the number of excitation events of the level 3^3P in 1 cm^3 in 1 sec on account of process (1) and on account of all remaining possible processes, in particular of direct excitation from the ground state O; $\bar{A}$ is the total probability of level's O radiative decay [*] $3^3P - 3^3S$ (λ 8446 Å). According to [1], p = 0.5.

Correspondingly to (2), the concentration of neon atoms in metastable state $^3P_0$ is

$$[\mathrm{Ne}^*] = W[\mathrm{Ne}]T, \qquad \frac{1}{T} = \frac{1}{\tau_0} + \frac{1}{\tau}, \tag{5}$$

whereas the number of photons 8446 Å, emitted in 1 sec in an atmosphere column with a 1 cm^2 base at heights greater than h_0 is

$$I_0 = A\int_{h_0}^{\infty} [\mathrm{O}^*]\,dh = \int_{h_0}^{\infty}\left\{q + p\frac{T}{\tau}W[\mathrm{Ne}]\right\}dh. \tag{6}$$

Let us compare two sub-integral terms of the expression in (6). The main contribution to q is evidently given by the direct excitation of the level 3^3P of oxygen by electrons. That is why, by order of magnitude

$$q \approx W'[\mathrm{O}], \qquad W' = n_e\langle v_e\sigma_e'\rangle, \tag{7}$$

where σ' is excitation cross section of the level 3^3P of oxygen by electron impact. Inasmuch as $[\mathrm{O}] \gg [\mathrm{Ne}]$, σ' and σ are quantities of same order, and $T \lesssim \tau$ (see below), we have

$$\alpha \equiv \frac{q}{pT/\tau W[\mathrm{Ne}]} \approx \frac{[\mathrm{O}]}{[\mathrm{Ne}]}\frac{\tau}{pT} \gg 1. \tag{8}$$

Thus, in stationary conditions the process (1), described by the second term in (6) does practically play any role. This process, however, may induce quite prolonged an afterglow, determined by the time T of metastable neon states' decay.

Assume, for example, that the primary flux of electrons drops from the constant value corresponding to stationary state (5), to zero. As is shown by observations of aurarae, the characteristic "cutting-off" time t_c of electron excitation (taking into account the lifetime of secondary electrons) may be less than 0.1 sec. During the time t_c the quantity q becomes

[*] insert the omitted words [...practically equal to the probability A of the transition...]

zero, while the glow intensity of the layer h, h + dh decreases by about α times (the quantity α depends apparently on h). At $t > t_c$ the glow of the layer h, h + dh is entirely determined by the excitation of the 3^3P oxygen level on account of the process (1), that is, it will damp with the time constant T. For a vertical atmosphere column above h_0, we obtain

$$I(t) = \int_{h_0}^{\infty} \frac{p}{\tau} [\mathrm{Ne}^*]_{\text{ст}} \exp(-t/T)\, dh, \tag{9}$$

where $[\mathrm{Ne}^*]_{CT}$ is the concentration of metastable atoms Ne in stationary conditions (5), preceding the "sutting-off" of the electron flux. It is assumed in (9) that $T \gg 1/A$. For the line λ 8446 Å this condition is knowingly fulfilled. The estimate of the quantity T will be given below. Let us now pass to the estimate of quantities τ and τ_0, entering (5). The dependence of the value of τ on height is determined, in accordance with (3), by the distribution of O_2 molecules in the atmosphere. The concentration of O_2 and the temperature may be given on the basis of the Harris-Priester model [4]. The cross section of the process (1), part of of formula (3), is $2.8 \cdot 10^{-15}$ cm^2 [1]. For the atmosphere model S = 200 the concentration of O_2, the temperature and the corresponding values of are compiled in the Table hereafter

h, км	T °K	$[O_2]$, см$^{-3}$	τ, сек	h, км	T °K	$[O_2]$, см$^{-3}$	τ, сек
120	350	$1{,}2\cdot10^{11}$	$7{,}2\cdot10^{-2}$	200	990	$7{,}5\cdot10^{8}$	6,7
140	630	$1{,}5\cdot10^{10}$	$4{,}2\cdot10^{-1}$	250	1080	$1{,}3\cdot10^{8}$	$3{,}9\cdot10^{1}$
160	800	$4{,}4\cdot10^{9}$	1,3	300	1130	$2{,}5\cdot10^{7}$	$1{,}9\cdot10^{2}$
180	910	$1{,}7\cdot10^{9}$	3,1				

The dependence of τ on height may be described with a precision sufficient for our purposes by the formula (In the region h $\sim$ 200 km)

$$\tau(h) = \exp\left[\frac{h-150}{H(O_2)}\right], \qquad H(O_2) \approx 27 \text{ км}. \tag{10}$$

The value of τ_0 is determined by the extinction of the metastable level of neon 3^3P_0 by electrons and other atmosphere particles (aside from O_2). The process (1) is quasi-resonance; as a consequence its cross section ($2.8 \cdot 10^{-15}$ cm^2) is very great. That is why $1/\tau_0$ could exceed $1/\tau$

apparently only in the case when the concentration of O_2 would constitute less than one percent of the total concentration of particles in the atmosphere, including the electrons, that is, at heights above 250 – 300 km. Consequently, for underlying layers, we may assume $T \approx \tau$.

It may be seen from the Table that the atmosphere layers below 150 km are de-excited for a time < 1 sec. Inasmuch as the observations with temporal resolution significantly better than 1 sec, present cosniderable difficulties, we may limit ourselves by the consideration of afterglows with a characteristic time greater than 1 sec. At the same time, we shall assume in (9) $h_0 = 150$ km.

The time interval of observations may be limited from above to several tens of seconds, The main contribution to afterglow intensity in that time interval is made by the atmosphere layers in the range from 150 to 250 ÷ 300 km, for which, as was shown above, $T \approx \tau$. Only an extremely weak, but lengthy afterglow is determined by higher atmosphere layers. This allows us to substitute T by τ in (9), leaving infinite the upper of integration. – To complete the integration, it is necessary to know in (9) the dependence of neon's and exciting electrons' concentration on height.

The distribution of neon concentratiin with height may be taken in the form

$$[\mathrm{Ne}] = [\mathrm{Ne}]_{h=150} \exp\left[-\frac{h-150}{H(\mathrm{Ne})}\right], \qquad H(\mathrm{Ne}) \approx 44 \text{ км}. \qquad (11)$$

The neon concentration in the upper atmosphere is little known, for its direct measurements at heights $h > 100$ km are absent, just as are the reliable theoretical computations for the transitional region between the mixing zone ($h \lesssim 90$ km) and the zone of diffusive separation ($h \gtrsim 120$ km). For the estimates, we shall admit that at 150 km the concentrations of O_2 and Ne differ by 10^3 times, that is

$$[\mathrm{Ne}]_{h=150} = 8 \cdot 10^6 \text{ см}^{-3}. \qquad (12)$$

Note, that it may be found possible to determine the Ne concentration in metastable state 3^3P_0 directly. If the considered region of the atmosphere is sunlit, fluorescence of Ne atoms in metastable state is possible, that would be analogous to helium glow in the line 10 830 Å [6, 7]. The Ne atoms in the state 3^3P must provide several fluorescence lines, of which the most intense will be the lines 6 266.495; 6 163.594 Å.

Let us examine in what way the flux of exciting electrons, and consequently, the quantities W and W', depend on height. As is well known, during a bright polar aurora the principal share of energy flux is generally borne by atmosphere-intruding primary electrons with energy of several kev. However, in order to explain the distribution of brightness with height in polar aurora rays, it is natural to assume the existence of a significant fraction of softer primary electrons (although other explanations of this effect are possible, in particular the significant increase of atmosphere density at great heights in the aurora region as a consequence of dynamic processes attending the intense heat liberation in the regions of glow). That is why we assume, for the sake of simplicity, that electrons with energies less than ~ 1 kev are usually absent in the primary flux of electrons intruding the polar atmosphere. Direct experiments speak in favor of such an assumption [8, 9], which, however, are still episodic. The path of electrons of a few kev in the atmosphere allows their penetration below the 130 km height. In this case we may estimate that at heights above 150 km the energy of intruding electrons varies insignificantly [10]. Consequently, the number of secondary electrons' birth events per single electron of primary flux will increase nearly proportionally to the rise of atmosphere density as the height decreases. Thus, the concentration and the flux of electrons, including the secondary electrons with energies $\gtrsim 20$ ev, providing the main contribution to W and W', must not, in the first approximation, depend on height. These considerations are corroborated by the results of measurement of photoelectron flux with energy > 40 ev, emerging in the atmosphere under the action of solar ultraviolet [11]. Indeed, the flux of such photoelectrons rises very slowly above ~ 200 km .

Obviously, a series of other factors still influence the dependence of W and W' on height. Thus, part of electrons of primary flux with great pitch-angles may undergo the magnetic reflection at sufficiently great height. Because of that (just as in the presence of primary electrons with energy $\lesssim 1$ kev) the flux of primary electrons may decrease with the height. The unknown distribution of electrons by pitch-angles hinders the attempts to estimate this effect. However, the experimental data, now available, are rather evidence in favor of significant isotropy of primary electrons and of invariability of their flux with height [10].

The relative concentration of secondary electrons is also difficult to estimate reliably, particularly in the region of sharp atmosphere content variation, that is, at heights from 100 to 200 km. It appears to be nonetheless probable, that the role of secondary electrons is determining and that W and W' either do not vary or increase with height.

Under these conditions the main contribution to $\langle v_e \sigma_e \rangle$ is made by electrons with energies of several tens of electronvolt. For electrons of such energies we may assume that the excitation cross section of the level 3^3P_0 (taking into account the cascade transitions) is $\sim 5 \cdot 10^{-18}$ cm^2.

Therefore we may admit for the lower estimate, that the flux of exciting electrons above 150 km does not depend on height and that

$$W \approx n_e \cdot 1.5 \cdot 10^{-9} \text{ cm}^3 \text{ sec}^{-1}.$$

Let us pass to the computation of the integral (9). According to (5), (10) and (11),

$$p\,[\mathrm{Ne}^*]_{\text{ст}} \frac{1}{\tau} \exp\left(-\frac{t}{\tau}\right) = pW\,[\mathrm{Ne}]_{h=150} \times$$
$$\times \exp\left\{-\frac{h-150}{H(\mathrm{Ne})}\right\} \exp\left\{-t \exp\left[-\frac{h-150}{H(\mathrm{O_2})}\right]\right\} = pW\,[\mathrm{Ne}]_{h=150} \times$$
$$\times\, \beta(h) \exp\left\{-\frac{h-150}{H(\mathrm{O_2})}\right\} \exp\left\{-t \exp\left[-\frac{h-150}{H(\mathrm{O_2})}\right]\right\}, \qquad (13)$$

where

$$\beta(h) = \exp\left\{(-h+150)\left[\frac{1}{H(\mathrm{Ne})} - \frac{1}{H(\mathrm{O_2})}\right]\right\} \approx \exp\left(\frac{h-150}{70}\right).$$

The multiplier β varies comparatively slowly with height: $\beta(150) = 1$; $\beta(300) = 8{,}5$. That is why during integration in (9) $\beta(h)$ may be substituted by the mean value $\bar{\beta} \sim 3$. After a similar simplification we shall have

$$I(t) = pW\,[\mathrm{Ne}]_{h=150}\bar{\beta} H(\mathrm{O_2}) \frac{1-e^{-t}}{t} \approx 5 \cdot 10^{-2} n_e \frac{1-e^{-t}}{t} \text{ rayleigh} \qquad (14)$$

where n_e is the concentration of secondary electrons with energies of several tens of ev in stationary conditions, preceding the isolation of the primary flux.

Formula (14) describes the afterglow of the vertical atmosphere column in the line 8446 Å in the course of several tens of seconds, beginning from about 1 second after the isolation of the primary flux.

In intense forms of aurorae n_e may exceed $\sim 10\ cm^{-3}$, which corresponds to tens and hundreds of rayleighs in (14). Therefore, at abrupt isolation of the primary flux of electrons, the line 8446 Å glow must decrease in time comparatively slowly after quick drop by about $\bar{\alpha} \sim 10^3$ times according to (14) [see (5), (12)]. A similar lag of line 8 446 Å emission by comparison with other allowed emissions was apparently observed [12].

The excitation of oxygen atoms as a result of the process (1) is endowed with still other certain specific peculiarities. Thus, simultaneously with the 3^3P oxygen level, the 3^5P one, intial for the line 7 774 Å, is being excited too. Laboratory measurements have shown that during excitation according to the scheme (1), that is in afterglow, the intensities of the lines 8446 and 7774 Å (in quanta) are related as 5 : 2 [1]. However, under low-pressure gas discharge conditions the line 7774 Å is usually more intense than the line 8446 Å. Although the conditions of these lines' excitation in a gas discharge and in the upper atmosphere differ considerably, it should be noted that in aurora spectra a relative intensity variation of the lines considered, by about from 3 : 1 to 1 : 3 was observed [3, 13].

In the process (1) about 0.6 ev pass to progressive degrees of freedom. Therefore, in afterglow the lines 8446 Å and 7774 Å are emitted by "hot" atoms, whose kinetic energy exceeds significantly kT. This must lead to the widening of line contour, distinct from the usual Doppler. However, because of the weakness of emissions, the observation of this effect is difficult.

A process analogous to (1) is possible also with the participation of argon atoms in metastable state 4^3P_0 (the radiation lifetime of this state is also infinitely great)

$$Ar(4^3P_0) + O_2 \rightarrow Ar(3^1S_0) + O(2^3P) + O(2^1S,\ 2^1D). \qquad (15)$$

The radiation lifetimes of the terms 2^1D and 2^1S are about equal to 100 and 0.7 sec respectively. That is why it makes sense to consider the possibility of line 5577 Å afterglow, beginning with the level 2^1S_0. Inasmuch as the cross sections of processes (1) and (15) are about identical [1], the time constant τ will be determined, as previously, by the Table and the formula (10). (We may neglect the small difference in the relative velocities). The calculation of line's 5577 Å afterglow is conducted in the same way as for the line 8446 Å. The difference consists in that $A \approx 1\ \mathrm{sec}^{-1}$ and the condition $T \gg 1/A$ is fulfilled for sufficiently high layers. That is why we have instead of (9)

$$I(t)=\int_{h_0}^{\infty}\left\{\frac{p}{\tau}[\mathrm{Ar}^*]_{\mathrm{cт}}\frac{A}{A-1/T}\left(e^{-t/T}-\frac{1}{AT}e^{-AT}\right)+qe^{-At}\right\}dh. \qquad (16)$$

No direct measurements of the relative fraction of atoms $O(2^1S)$ and $O(2^1D)$ in the process (15) wew made; however, one may assume that $p \sim 0.3$. The excitation cross section of the level 4^3P_0 of argon by electrons must be about the same as for the level 3^3P_0 of neon. In the given case we may assume $\beta = 0.5$. Indeed, $\beta(h)$ decreases with height.

The concentration of Ar atoms at heights $\lesssim 90$ km is significantly greater that that of neon atoms. In the region of diffusive separation ($h \gtrsim 110 - 120$ km), and because of difference in atomic weights, the concentration of argon decreases with height substabtially faster than that of neon. In spite of this, there is still about 2 orders more of argon than neon at the height of 150 km. That is why we may assume $[\mathrm{Ar}]_{h=150} \approx 8\cdot 10^8\ \mathrm{cm}^{-3}$

It may be seen from formula (16) that during the first few seconds after primary flux' isolation the terms proportional to e^{-At} will damp. Subsequent afterglow of the vertical column of the atmosphere is described by a formula analogous to (14). Substituting in (16) the corresponding numerical values and assuming $A/(A-1/T) \approx 1$, we shall obtain

$$I(t)=pW''[\mathrm{Ar}]_{h=150}\bar{\beta}H(\mathrm{O}_2)\frac{1-e^{-t}}{t}=5\cdot 10^{-1}n_e\frac{1-e^{-t}}{t}\ \text{rayleighs} \qquad (17)$$

Here $W''-n_e\langle v_e\sigma_e''\rangle$ is the probability of argon's level 4^3P_0 excitation.

The measurement of the course of line 5577 Å intensity drop after the excitation pulse was conducted only in the course of the first few seconds with the view of determining the lifetime of oxygen level 2^1S_0 in the atmosphere [14, 15]. Apparently, for that line, just as for 8446 Å further, more detailed and extended measurements of the course of intensity drop would be necessary to determine the lifetime of argon and neon atoms in metastable state. From such measurements and also by these atoms' fluorescence more founded estimates of argon and neon concentration in the upper atmosphere can be made. The described processes may also play a part in the "wind-cone effect" of the afterglow tail after rapid shift of the exciting electron beam relative to the glowing region of the atmosphere [16], and, moreover, in the formation of the diffusion background of luminescence, surrounding the bright forms of aurorae [17], on account of diffusion of argon and neon metastable atoms from the excitation region.

The processes of energy transfer in the upper atmosphere at collisions with participation of atoms and molecules in metastable states deserve a serious attention, inasmuch as the basic atmosphere constituents, such as N_2, O_2, O, N, Ar, Ne and He, have metastable levels with significant lifetimes.

**** THE END ****

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